Optimization of Drilling Parameters for PDC Bit Drilling Medium-to-Hard Formations

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ABSTRACT

The cost of drilling geothermal wells is significant. To reduce the drilling cost, it is essential to improve ROP (rate of penetration) and reduce NPT (non-productive time). Although PDC (polycrystalline diamond compact) bits have been promoted for use in geothermal well drilling, choosing drilling parameters such as WOB (weight on bit) and bit rotational speed is difficult for medium-to-hard geothermal formations. The optimum WOB and bit rotational speed are usually determined by drill-off tests at drilling sites. If optimum WOB or bit speed can be predicted in advance, it is believed that NPT can be reduced with a sufficiently high ROP. The objective of this study is to determine optimum drilling parameters for drilling medium-to-hard formations with PDC bits based on numerical simulations.

Numerical rock cutting simulations were carried out for a PDC cutter using the 2-dimensional particle flow code PFC2D, a discrete element simulator. In this study, existing simulation script code was modified to be able to apply an arbitrary weight on a PDC cutter. The simulation procedure consists of three steps: 1) creation of a synthetic rock specimen with bonded particles, 2) uniaxial compression tests on the synthetic rock specimen to calibrate mechanical parameters used in the synthetic rock model, and 3) rock cutting tests using a single PDC cutter. The simulation results showed that the PDC cutter penetrates deeper into the rock surface with a higher WOB, resulting in a higher ROP. The number of cracks created in the rock by the cutter increased (approximately) linearly with the WOB.

1. Introduction

Drilling is the most expensive part of oil and gas and geothermal development. Taking geothermal development as an example, it is generally estimated that more than JPY 25 billion is required to build a 30,000 kW geothermal power plant. Of this amount, approximately JPY 7 billion is for underground investigation and exploration, most of which is for well drilling (JOGMEC, 2022). If the cost of drilling wells can be reduced, geothermal development can be promoted. To reduce the cost of drilling wells, it is essential that drilling operations are completed in a short time, and technology has been developed over the past 100 years to achieve this. One solution has been the development of PDC bits. PDC bits have been used in oil and gas exploration and are characterized by higher drilling speeds and longer bit life than the conventional roller cone bits. However, PDC bits are designed for oil and gas drilling and are not suitable for geothermal drilling. The rock in geothermal wells is hot and hard, making drilling with PDC bits difficult. The optimum weight on bit (WOB) and bit rotation for drilling is determined by a drill-off test, which can only be carried out in the field, but it is believed that if either the bit load or rotation speed can be predicted, drilling operations can be shortened. Therefore, the aim of this study is to determine the optimum bit load for drilling medium hard rock with a PDC bit from simulations.

2. Numerical Simulation

The rock cutting simulation in this paper is carried out using PFC2D, developed by Itasca; a description of PFC2D is given later. The process for rock cutting simulation is in the following order: creation of a rock grain model, calibration of the grain model by UCS testing, and then cutting simulation.

2.1 Distinct Element Method

The Discrete Element Method (DEM), usually referred to as the Discrete Element Method, is a computational method for calculating the motion and effects of a large number of particles, a numerical method developed by Cundall in 1971 for the analysis of rock mechanics problems, and further refined by Potyondy and Cundall in 1979. Today, DEM is widely used as an effective method for solving engineering problems in granular and discontinuous materials, especially in granular flow, powder mechanics and rock mechanics.

2.2 Particle Flow Code in 2 Dimensions

PFC2D is a general purpose discrete element modelling framework developed by itasca, including a computational engine and graphical user interface. the PFC model simulates the motion and interaction of a large number of finite size particles. Particles are rigid bodies of finite mass that can move independently and can both translate and rotate. Particles interact by contact through internal forces and moments. The motion of these mass-bearing particles also follows Newton's equations of motion.The PFC model consists of a body and contact points, and the body is divided into three types: ball, lump and wall. A ball is a rigid disc of unit thickness, while a clump is a collection of pebbles and consists of a rigid disc of unit thickness. A clump models a rigid body of any shape. The pebbles that make up a clod may overlap, but there is no contact between them. Walls are straight segments and are treated as boundaries. Contact models specify the opportunistic properties of contact and the interaction between contact components. They support relative motion and load transfer between elements. The coupling model used in this paper is the linear-parallel bond model. From this, the particles in the granular model are bonded together at the contact points via the linear-parallel bond model.

2.3 Liner-Parallel Bond Model

A formulation of the particle coupling model has been proposed by Potyondy and Cundall (2004). As shown in the figure 1, the parallel bond model is represented by a spring with constant stiffness in the normal and tangential directions to the contact surface. The linear parallel bond model can be divided into a linear part (uncoupled state considered as a linear contact model) and a parallel bonded part (coupled state considered as a linear parallel bond model), where the parallel bonding acts like an elastic beam or glue with both shear and tensile strength. Contact couplings transmit only forces, whereas parallel bondings transmit both forces and moments. The stiffness of the contact surfaces transmits the forces and moments caused by the relative motion between adjacent particles. The interaction forces along the normal or tangential direction in these contacts are linear and are determined by both stiffness and stiffness ratio. If the maximum stress exceeds the corresponding bond strength, the parallel bond will fail. The breaking of the bond removes the tensile strength and from that point the parallel bond model changes to a linear model. In the uncoupled state, only the linear model plays a role at the contact surface and no longer resists relative rotation. This process is manifested macroscopically as rock fracture and the linear parallel bond model is used to model rock samples.

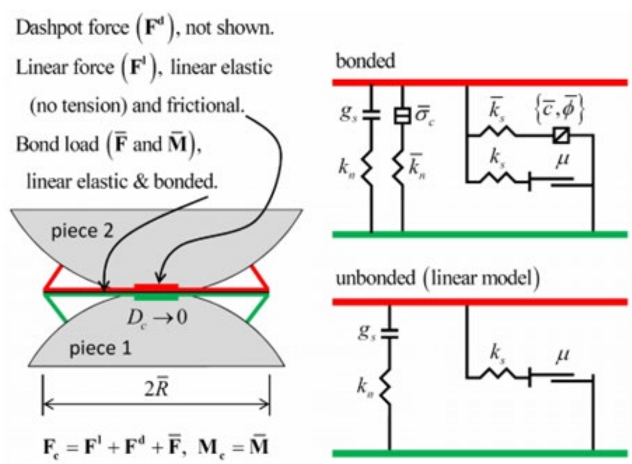

Figure 1: Schematic of the modified bonded particle model (Material-Modeling Support for PFC, 2021).

2.4 Material Calibration

Carthage limestone was selected as the rock for the study. The grain model was generated using a modelling package provided by itasca. This package supports the generation of rectangular rock specimens consisting of individual grains with specified micro-parameters. The micro-parameters were calibrated by comparing actual rock properties of the Carthage limestone (literature values) with the results of numerical simulations of uniaxial compression tests (UCS) on the grain model. The micro-parameters entered into PFC2D are shown in Table 1. The rock-grain model created is also shown in Figure 2. The density of the particles is an important parameter as it affects the overall rock dynamics. The value given for the density of the rock is 2630 kg/m3. Parallel bonds, which simulate the effect of cementation between particles, will fail if either of the following two criteria is met 1) the shear contact force exceeds the shear strength of the parallel bond, or 2) the vertical contact force exceeds the tensile strength of the parallel bond. When a parallel bond fails, its contact stiffness is no longer valid. The values of shear and tensile strength of parallel bonds between particles in the generated granular model are not constant. The values follow a normal distribution across all particles. The mean value for both parallel shear and tensile strength is given as 116.0 MN with a standard deviation of 20.0 MN for both. The particle sizes follow a normal distribution with a ratio of 1.66 between the largest and smallest particle size. The minimum particle size is determined to be 0.485 mm. The PFC2D modelling package includes tools to simulate UCS tests on the generated grain models and to measure stresses and strains in the grain models. To obtain values for uniaxial compression, Young's modulus and Poisson's ratio of the granular model, a UCS test is performed by clamping the top and bottom of the granular model between the walls at a constant speed of 0.05 m/s. It was performed on a granular model with dimensions of 50*100 mm and a minimum particle size of 0.485 mm. Figure 2 shows the obtained stress-strain diagram and the table 2 shows the obtained values of uniaxial compressive strength, Young's modulus and Poisson's ratio. The obtained properties of the grain model are compared with those of the actual Carthage limestone. Both the red and blue lines indicate that the parallel bonds between the grains have been broken, the red line meaning that the parallel bonds have been broken by tensile failure and the blue line meaning that the parallel bonds have been broken by shear failure.

Table 1: Calibrated micro-parameters of rock model.

Height ,H (mm)	**mv_H**	**100**
Width ,W (mm)	**mv_W**	**50**
Minimum radius (mm)	**ba_min**	**0.485**
Ball size ratio	**mg_ratio**	**1.66**
Modulus (GPa)	**pbm_emod**	**83.0**
Normal to shear stiffness ratio	**pbm_krat**	**3.8**
Porosity	**pk_nc**	**0.1**
Bulk density	**cm_densityVal**	**2620**
Damping ratio	**cm_localDampFac**	**0.7**
Bond Modulus (GPa)	**pbm_bemod**	**83.0**
Bond Normal to shear stiffness ratio	**pbm_bkrat**	**3.8**
Tensile strength (MPa)	**pbm_ten**	**116±20**
Cohesion (MPa)	**pbm_coh**	**116±20**
Radius multiplier	**pbm_rmul**	**1.0**
Friction angle	**pbm_fa**	**0**

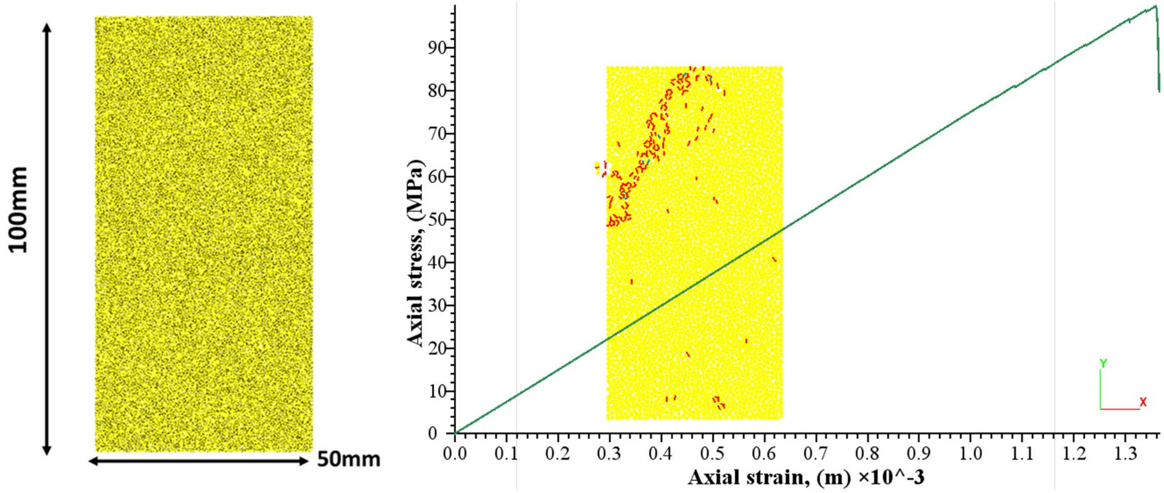

Figure 2: Rock grain model (left) and stress-strain diagram (right).

Table 2: Comparison of physical properties of actual rocks and rock granular model.

	Carthage Lime stone	Granular Specimen	Error ratio (%)
Young's modulus, E (GPa)	76	75	1.3
Poisson' ratio, v	0.29	0.30	3.4
Peak strength, (MPa)	-	101	-

Errors in Young's modulus and Poisson's ratio between the actual rock and the granular model of the Carthage limestone were within 5%. This confirms that the Carthage limestone is correctly modelled by the granular body and that the granular body model is a crack-free rock model with a strength comparable to that of the Carthage limestone.

2.5 Cutting Simulation

A numerical model has been built to simulate the cutting process. The model uses a single PDC cutter to cut a granular model of rock. The cutter cuts the rock due to a constant horizontal speed, while at the same time a vertical load is applied to the cutter. A schematic diagram of the cutting environment is shown in Figure 3.

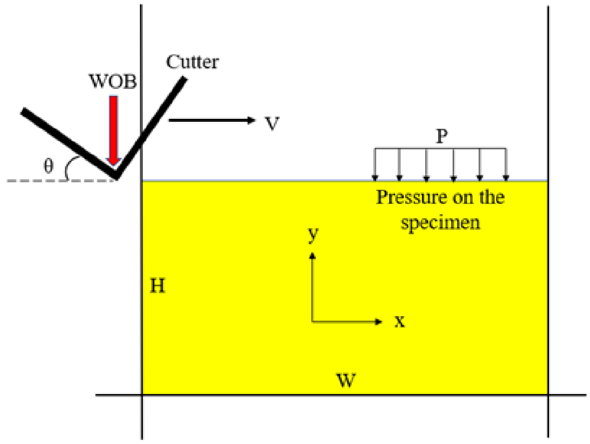

Figure 3: Schematic diagram of the rock cutting environment.

Rock-cutting simulations were performed using the actual drilling conditions of a typical geothermal well. The drilling conditions are listed in Table 3.

Table 3: Cutting simulation conditions.

Drilling depth, (m)	3000
Mud water density (kg/m^3)	1000
Bottom hole pressure (MPa)	30
Bit size (inches)	8−1/2
Bit rotation speed (rev/s)	2
Number of PDC bit cutters	49
Weight On Bit (tf)	2～20
Back rake angle （°）	20
Cutter diameter (mm)	10.0
Cutter velocity (m/s)	1.4
Cutting distance (mm)	100

The side and bottom boundaries of the section model are created by walls, one of the elements of PFC2D. The granular model is held and constrained by the wall. In order to model the mine bottom pressure in the cutting model, the created granular model was compressed from the top until the target compressive stress was reached. As cutting with PDC bits is generally carried out in the range of WOB 2~20 tf, the simulation in this study was set in this range. The cutter model is a rigid body composed of lumps. The clumps can create arbitrarily shaped particles and simulate free-form materials. The cutter is first placed on a rock sample. One of the most important properties of the cutter is the back rake angle. In this case the back rake angle is set to 20°. The coefficient of friction of the cutter is an important physical parameter. The coefficient of friction is the factor that controls the maximum allowable shear contact force between two DEM elements. For the same cutter load, a cutter with a higher coefficient of friction is more likely to have a higher horizontal force value. The cutter coefficient of friction is set to 1.5. As the cutters are rigid in this model, no compliance or modulus of elasticity is required; the assumption of a rigid body is perfectly reasonable as the modulus of elasticity and UCS values of the PDC are several orders of magnitude higher than those of the rock. The cutter is subjected to a vertical force due to the WOB. In PFC2D all modelling is based on a 2D approach where all circular particles have a 3D interpretation, such as a cylinder with a circle extruded from it, and all forces and constants are based on this virtual per unit thickness of the cylinder. The loads on the cutters are set by assuming that the cutters of the bits in contact with the anti-bottom are in the same horizontal plane and that the loads due to the WOB are uniformly distributed. The model assumes a unit thickness of the cutter (1 m), so that, for example, a load of 1 kN applied to the actual cutter will result in a force of 100 kN/m (=1 kN/cm) in the PFC2D model.

2.6 The Effect of WOB on Rock Cutting

Cutting simulations were carried out at WOB of 2, 5, 10, 15 and 20 tf. Cutting behaviour and crack propagation in a 40 mm cut are shown in Figure 4.

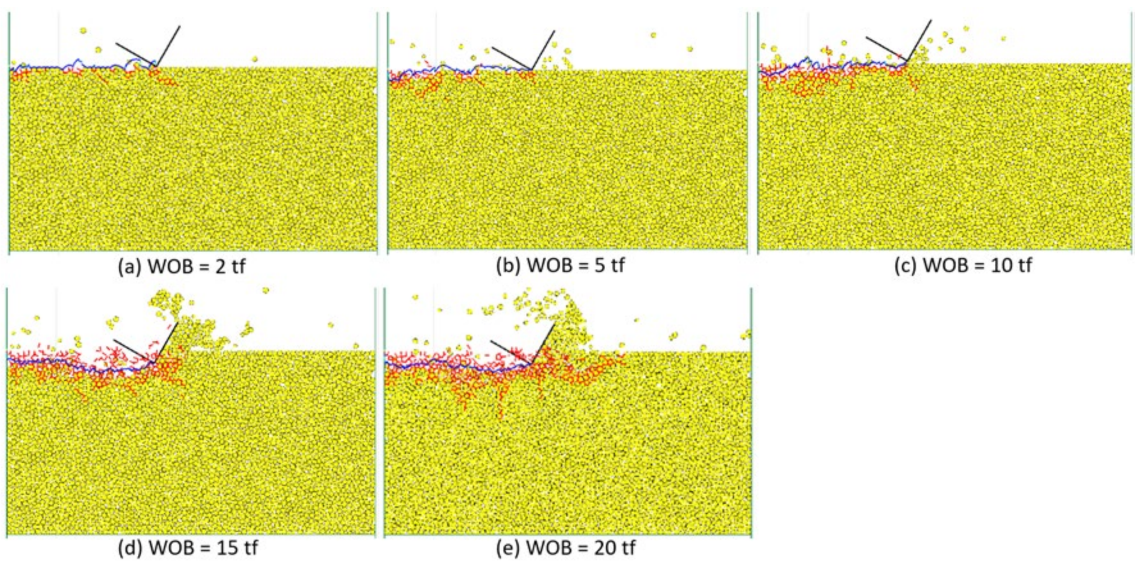

Figure 4: Cutting behavior and crack propagation.

The number of cracks produced, the maximum ROP and the average force applied to the cutter obtained from the cutting simulation are shown in Figure 5, 6 and 7 below.

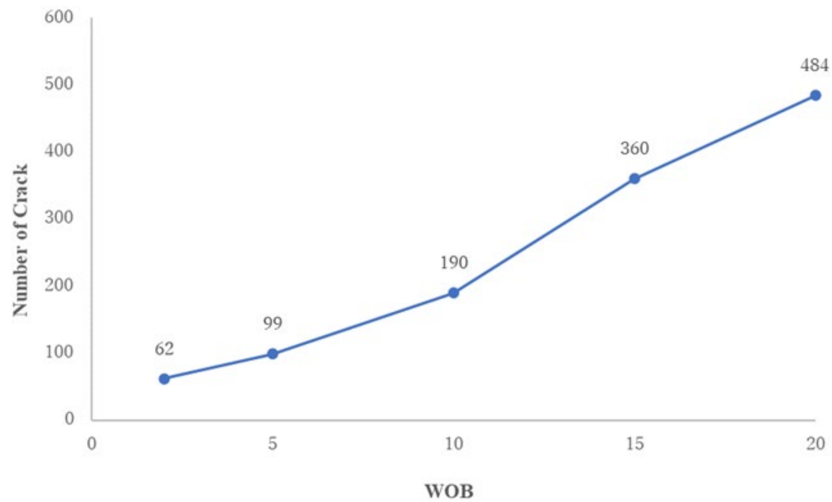

Figure 5: Number of cracks for each weight on bit (WOB).

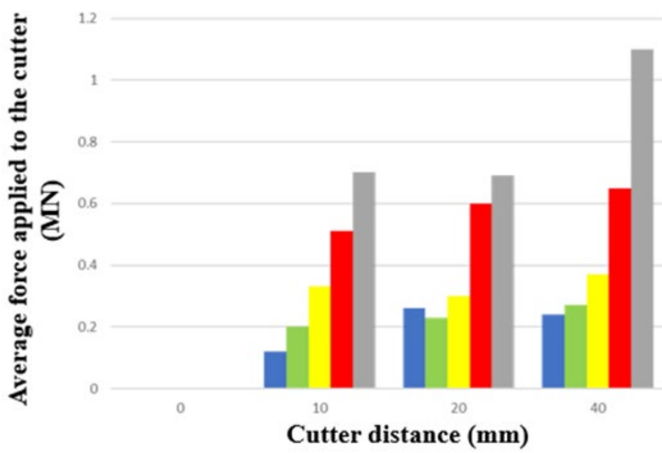

Figure 6: Average force to cutter vs. cutting distance.

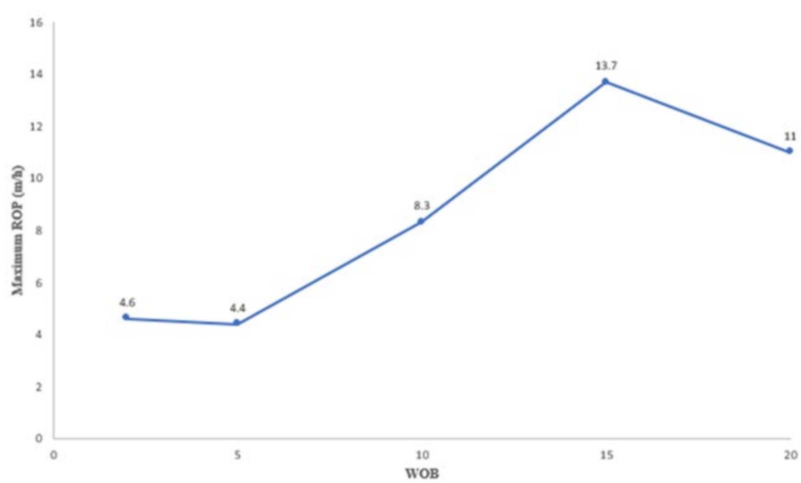

Figure 7: Maximum digging rate at each weight on bit (WOB).

The figure and table show the rock surface and the cracks inside the rock: at WOB 20 tf the cracks are not only in contact with the cutter, but also more inside the rock and in front of the cutter, where the number of cracks is highest. It can also be seen that the cracks become deeper and more numerous as the WOB increases. As the cutting distance increased, the force applied from the granular model to the cutter increased significantly from WOB 15 tf, with the highest value at WOB 20 tf, suggesting an increase in the vertical downward force with increasing WOB and the influence of debris accumulated in front of the cutter as a result of cutting. It can be predicted that the cutter wear rate increases significantly from a WOB of 15 tf. The maximum ROP results were highest at 15 tf. As this is the value at maximum cutter penetration during the cutting process, it does not mean that the overall ROP is higher at 15 tf, but it does show a significant increase in ROP from 10 tf to 15 tf. In terms of the results for maximum ROP and average force applied to the cutter, the 15 tf WOB case is considered superior.

3. Conclusions

In this study, suitable bit loads for excavating medium-hard rock with PDC bits were investigated by rock cutting simulations using PFC2D while varying the bit load. Three things can be said from this study.

- For drilling in medium-hard rock with 8-1/2-inch diameter PDC bits, the WOB should be 15-20 tf.
- The higher the bit load, the better the PDC cutters bite into the rock and they excavate the rock more efficiently. However, high bit loads result in faster cutters wear.

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